

LESSONS LEARNED IN OPERATING THE HOSE- IN-HOSE SYSTEM FOR TRANSFERRING SLUDGE AT HANFORD'S K BASINS

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Project Hanford Management Contractor for the
U.S. Department of Energy under Contract DE-AC06-96RL13200

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LESSONS LEARNED IN OPERATING THE HOSE-IN-HOSE SYSTEM FOR TRANSFERRING SLUDGE AT HANFORD'S K BASINS - 8236

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ABSTRACT

In May 2007, the Department of Energy and the Fluor Hanford K Basin Closure Project completed transferring sludge from the K East Basin to new containers in the K West Basin using a Hose-in-Hose system. This project presented a number of complex and unique technical, operational, and management challenges that had to be resolved to complete the required transfers and satisfy project milestones. The project team (including DOE; regulators; and Fluor management, operations, maintenance, engineering and all other support organizations) found innovative solutions to each challenge.

This paper records lessons learned during the operational phase of the sludge transfer via the Hose-In-Hose system. The subject is limited to the operational phase and does not cover design, development, testing or turnover. A discussion of the situation or problem encountered is provided, along with the lesson learned as applicable to a future program or project.

INTRODUCTION

The two K Basins at Hanford, Washington were placed into service in the 1950s as temporary holding facilities for spent fuel from the K reactors. Each K Basin measures 38 meters (125 feet) by 20 meters (67 feet) and holds 4 million liters (1.1 million gallons) of water. The two concrete basins sit less than 450 meters from the Columbia River and were originally unlined concrete structures with a design life of 20 years. The K East (KE) and K West (KW) defense production reactors were shut down in 1971. [1]

Until 2004, the K Basins held the largest collection of spent nuclear fuel in the United States Department of Energy (DOE) complex — over 1.8E6 TBq (50 million curies) of radioactivity. During the years of fuel storage, water leaked from the KE Basin through a construction joint. This release of radioactive material to the environment increased the urgency for removing the fuel, sludge, debris, and water from the KE Basin so that it can be demolished and the soil under the facility can be remediated.

In late 2004, Fluor completed the safe removal of more than 100,000 fuel elements. The 2,100 metric tons (4.6 million pounds) of fuel were placed into dry storage far from the Columbia River. A significant fraction of the fuel stored in the KE Basin degraded due to breaches of the cladding that occurred not only from physical handling during reactor discharge, but also from corrosion during long-term storage under water in open canisters. Over time, corrosion products from degrading fuel rods, storage racks, concrete basin walls, organic material, and environmental particulates accumulated as sludge in the fuel canisters and on the floor of the KE Basin (see Figure 1). Sludge in the K Basins is defined as material smaller than 0.635-cm (0.25-inch) diameter.

Fluor began vacuuming sludge from the floor of the KE Basin in October 2004. The sludge retrieval process used submersible pumps to vacuum the sludge into newly constructed steel containers that were submerged in the basin. To retrieve the sludge, operators manipulated specially designed vacuum heads at the end of long pole tools as they stood on grating suspended above the basin water. The pumping system included a strainer to ensure material larger than 0.635 cm (0.25-inch) did not reach the sludge containers.

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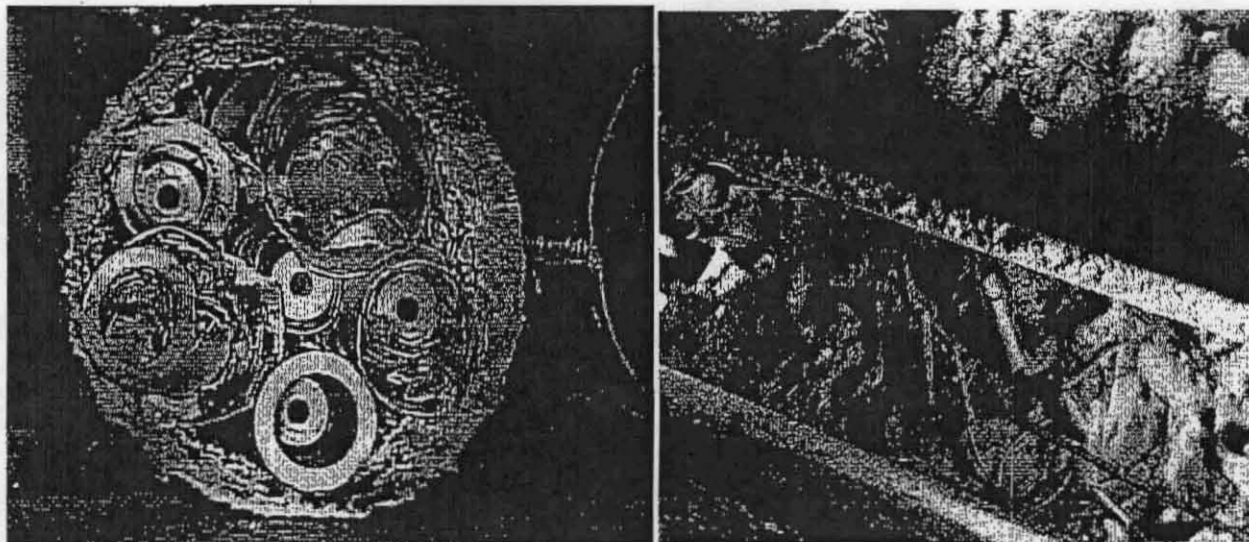


Fig. 1. Hanford's K East Basin had badly corroded fuel (left) and sludge (right).

After the sludge in the KE Basin was collected in the engineered containers, it was pumped to new containers submerged in the KW Basin via a Hose-In-Hose (HIH) system. The sludge transfer began in October 2006, and all sludge was transferred in May 2007. Sludge in the KW basin has also been vacuumed into new containers where it will be stored pending treatment and disposal.

HOSE-IN-HOSE SLUDGE TRANSFER SYSTEM

The HIH system retrieved the sludge from containers in the KE Basin, injected dilution water as necessary to control slurry concentration, and pumped the slurry to containers in the KW Basin. The simplified sketch in Figure 2 depicts the system. The four outdoor primary booster pumps (P-301, P-302, P-303, and P-304) were enclosed in containment structures (booster pump stations). Each of the stations also included an installed spare pump that could be used in the event that the primary pump in that station failed. The sludge transfer hose installed above water was a hose-inside-hose configuration: the inner or transfer hose was 3.175 cm (1.25-inch) diameter, contained inside a 10.16 cm (4-inch) diameter outer hose.

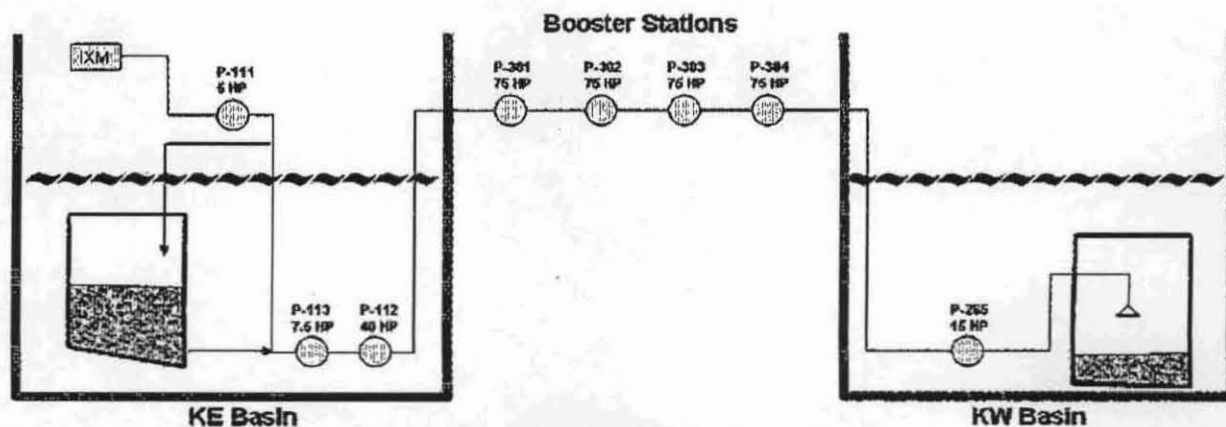


Fig. 2. This schematic is a simple illustration of the HIH Sludge Transfer System.

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The concentration of the solids in the slurry was controlled by adjusting dilution water based on feedback from an in-line suspended solids instrument.

HHH OPERATIONAL LESSONS LEARNED

There is only one thing more painful than learning from experience, and that is not learning from experience. ~Laurence J. Peter

Operation of the HHH system provided a wealth of experience and lessons learned. A summary of some of the more significant operational lessons are provided in the remainder of this paper. [2]

Bottom Suction Retrieval, Dilution Strategy, and Sparging

Retrieval of sludge from the KE containers was completed via suction from the bottom outlet of the container. The solids feed rate was not constant and depended on the formation of the sludge inside the tank and the effectiveness of tank sparging. Mobilization of the sludge was crucial to getting the sludge out of the containers.

The HHH design injected dilution water via a pipe with its discharge located a few centimeters above the outlet at the bottom of the container. Additional dilution water was added downstream from the container based on feedback from instrumentation measuring suspended solids to maintain a nominal slurry concentration of approximately two percent by volume. The operational concept was to allow the system to operate in automatic mode until the sludge near the tank discharge was removed and indicated solids concentrations were low. Then, mechanical action and/or sparging (water spray) would begin to fluidize sludge from the back of the container and move it toward the tank outlet.

Figure 3 shows views of a typical KE sludge container. Support structures and other equipment (e.g., sludge distributor, level monitor probes) inside the container obstructed sparging activities that used water lances inserted through a hole in the basin grating, down through the slotted hole in the tank covers. One sparge lance was used for each of the six openings. Three tanks were smaller as shown in Figure 3; a fourth tank was much larger. The fourth tank had 16 holes provided for sparge lances.

Once the bulk of sludge was removed from a container using the sparge lances, high pressure water lances were installed in the container to wash the remaining sludge to the outlet. In testing, this process worked well.

In actual operation the bottom retrieval method was challenged by factors not considered in design and testing. First, a field modification during construction resulted in a condition where the internal dilution pipe did not extend low enough to properly dilute the sludge at the container discharge. This situation was not discovered for several days after sludge retrieval began. Once the dilution lance was lowered to the intended location, the ability to agitate, dilute, and mobilize the sludge in the container was greatly improved.

Second, additional piping was added after testing had completed. Hoses, pipe elbows, and a three-way valve were added on the discharge of each pair of containers to simplify switching between containers. Adding this additional head loss on the suction side of the first slurry pump made it more difficult to retrieve sludge from the container.

Third, foreign material/debris items that were inadvertently dropped into the sludge container hampered the sparging efforts at the end of tank transfers. Also, the gentle slopes of the bottom of the containers made mobilization of sludge to the container outlet difficult.

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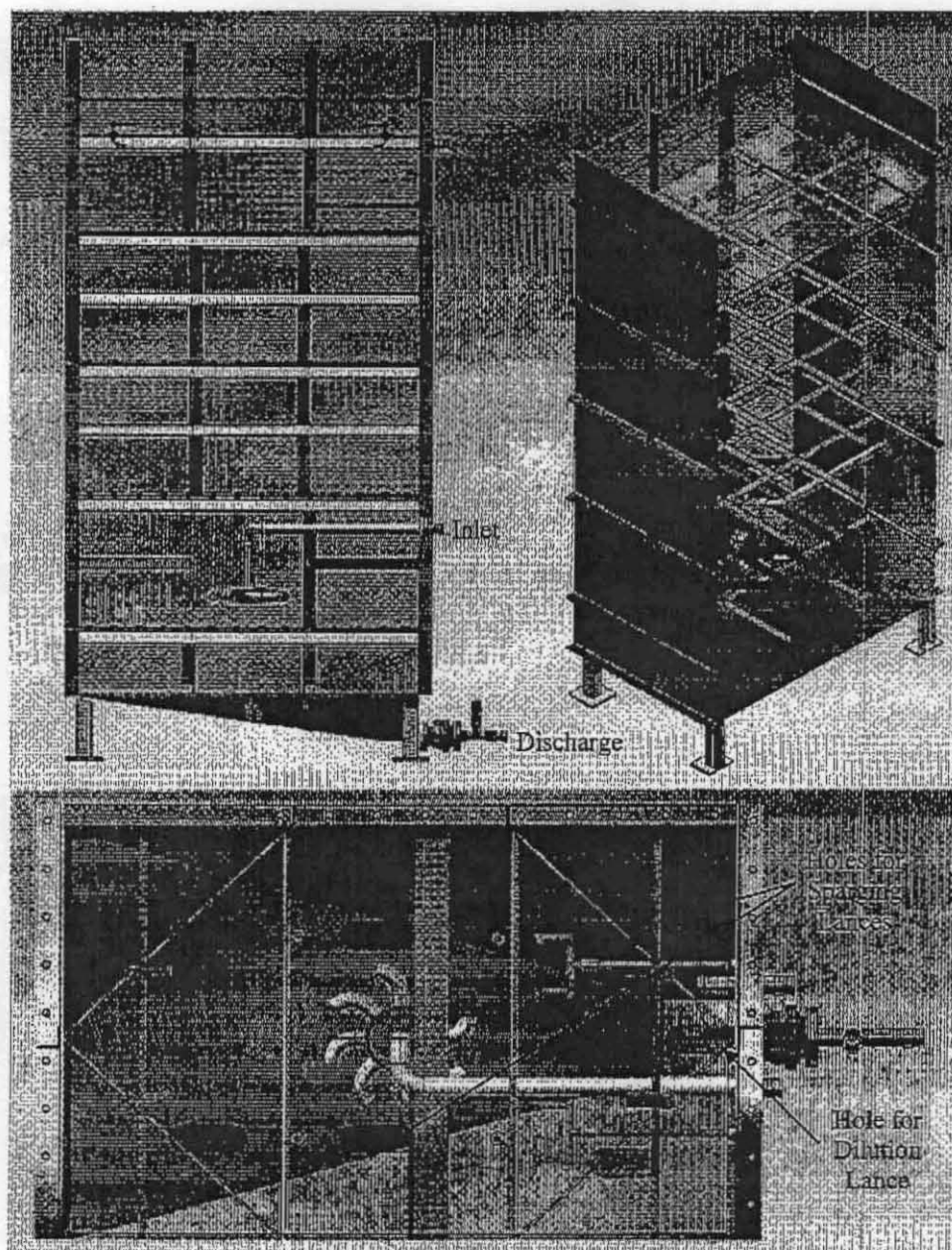


Fig. 3. These schematics show side, top, and isometric views of a typical KE sludge container.

Finally, high-pressure washers using small orifice spray tips often became clogged or plugged, most likely due to actions to physically move sludge with the lance when the water was not flowing, or pressing the tip into the sludge to break up mounds.

Lessons

Mobilizing the sludge inside the tank is crucial to obtaining good flow out of the discharge. A permanent dilution source should be integral to the container to ensure that the dilution water will be added at the critical location to mobilize sludge. Physical agitation should be considered instead of water spray.

Container bottoms should slope at a steep angle toward a bottom discharge, consistent with the angle of repose for the sludge materials.

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Internal structural elements should be kept to a bare minimum (possibly design to remove a distributor after the tank is filled). These items make it difficult to use tools that can reach the sludge. Irregular shapes also allow sludge to collect in areas that are difficult to reach and clean.

Engineered and administrative controls to prevent foreign material from entering the containers during all stages of construction and operations are essential.

If water sparging is to be used, the water source should be a separate source from the water used to dilute the slurry. The HIH design that shared the source water proved to be inefficient and created a number of operational problems. The act of diluting the slurry stream needs to be completely decoupled from the methods necessary to move sludge to the discharge of the tank.

Foreign Material in Sludge Containers

Unexpected foreign materials in the sludge containers in KE proved to be a significant challenge. Design requirements and the design/testing did not address this potential. Coarse strainers and basket strainers added to the HIH system to address foreign material created additional challenges for system operation.

To fill the KE sludge containers, the sludge was pumped through safety-significant strainer baskets to prevent fuel pieces larger than 0.635-cm (0.25-inch) from reaching the containers. However, during the installation of the containers, and during transition between filling the containers and preparing them for emptying, the containers did not have covers. Either during construction or later when installed covers were removed, foreign material was introduced to the containers. Foreign material included nuts, writing pens, plastic, rags, tape rolls, lights and cords. The smaller foreign material created pump obstructions and larger material blocked sludge from the outlet of the tanks.

Flushing and removing these items caused delays in processing and drove the addition of coarse strainers at the container outlets to prevent damaging the transfer pumps. The addition of coarse strainers (Figure 4) caused additional operational issues due to pressure drops and plugging.

A variety of flushing methods were employed depending on the specific problem encountered. Back flushing was not designed into the system. Some flushing required the preparation of work packages and the reconfiguration of the hoses/pumps, while others required valve sequences that were incorporated in the operating procedures. In all cases, stopping the sludge transfer to perform a flush was time consuming and had a significant effect on the efficiency of the HIH system.

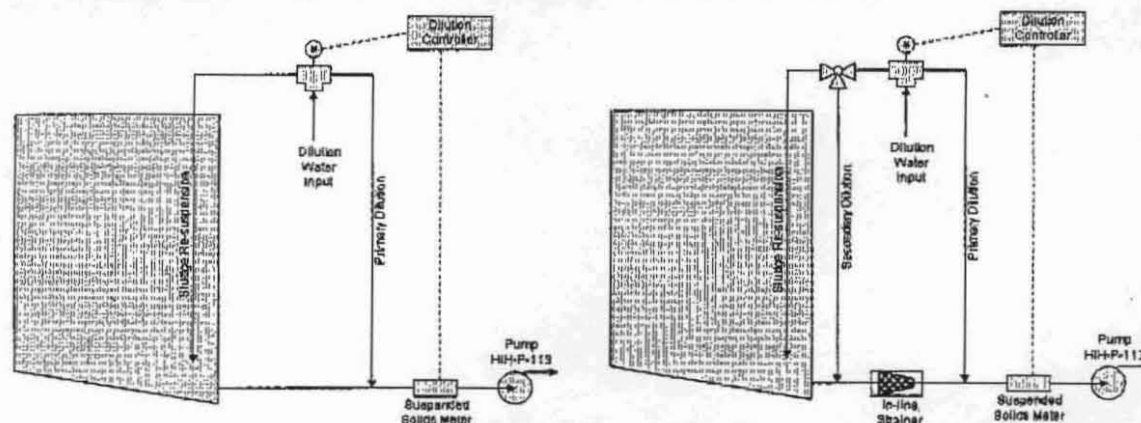


Fig. 4. This diagram shows the configuration of the HIH system before and after an in-line coarse strainer was added.

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Lessons

Although the process of filling the containers restricted fuel pieces (and therefore debris items) larger than 0.635-cm (0.25-inch), foreign debris material was not positively excluded by engineered barriers at the top of the containers. Design specifications should account for foreign material in the sludge.

Administrative procedures were developed during the HIIH operations to prohibit additional foreign material from getting into the containers when the covers and settler tubes were removed, but these administrative methods were not fully effective in preventing foreign material from entering the system.

The original design should incorporate back-flushing capabilities. During HIIH, back-flush operations were possible only through creativity and hard work, swapping underwater hoses. A great deal of time could have been saved if design and operations had accounted for back-flushing.

Suspended Solids Metering

Accuracy of the suspended solids meter in the HIIH system was problematic for tracking the volume of sludge transferred.

The HIIH transfer system retrieved sludge from the KE storage containers by diluting the sludge slurry to a set percentage of solids for delivery to the transfer pumps. Maintaining solids content within specified limits was essential to achieving the design sludge transfer rate, protecting the system from too high a sludge concentration, and maintaining assumptions of the approved safety analyses. Once the transfer of sludge began, the basin water became too cloudy to observe sludge levels in the tanks. Without visual evidence of sludge levels, the suspended solids meter was used to estimate changing sludge volumes in the supply container and receipt container. During operation of the HIIH system, the solids measurement instruments were also used to provide feedback to operators who were using water lances to mobilize sludge in the KE sludge supply tanks. In addition, wear rates of the transfer pumps were monitored based on volume of slurry transferred through the pumps.

The HIIH suspended solids meter consistently provided an output higher than the actual solids contained in the slurry. This error was revealed after comparing observed volumes collected in the receiving containers with the volume calculated as transferred using the solids instrument readings. The magnitude of the error appeared to vary considerably depending on operating conditions of the transfer system. The ratio of the indicated to the actual solids concentration ranged from four to ten throughout the transfer campaign. The error was observed to be smaller when the feed of solids from the source container was consistent and the inlet pressure on the first transfer pump was stable, and larger under changing conditions, especially when plugging of the container outlet was suspected.

One of the most likely contributors to the error was gas bubbles in the slurry stream. Gas bubbles could be seen as false solids by the ultrasonic attenuation detector. Bubbles could have originated in the dilution water or as a result of cavitation during pressure/vacuum oscillations.

To help confirm solids transfer, a portable radiation detector was placed adjacent to the slurry line. Adding this instrumentation provided useful feedback to operators in assessing whether or not the slurry contained sludge or the suspended solids meter was reading falsely due to suspect conditions described above. The radiation instrument provided only a gross indication, but was still beneficial in assessing the system's performance.

Lessons

An ultrasonic instrument to measure solids should not be located where it is subject to oscillations of pressure/vacuum. Placing the instrument at the discharge of the first transfer pump rather than at the suction, could possibly have eliminated a large portion of the error observed.

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When using an ultrasonic or optical instrument, preclude sources of air entrainment in the slurry stream that could cause false readings.

A radiation monitor that measures slurry radioactivity provides useful feedback of the system's performance, and should be included in the design.

Using two types of solids instruments (e.g. ultrasonic and mass flow) should be considered. Neither instrument on its own provides complete information (solids concentration and density) needed to eliminate having to make assumptions regarding properties of the waste being transferred. Use of both indications could provide better information for assessing system performance and determining the volume transferred.

Estimates of the duration required to transfer the KE sludge were based on the expected suspended solids in the slurry. Actual transfer rates were significantly less than those assumed during design. Analyzed accident consequences and resulting controls were developed using assumed solids content in the slurry, and appeared to be overly conservative. Future projects should consider the potential for errors in process data and evaluate the sensitivity of those errors on the operational timelines and accident analyses.

Pump Wear Failures and Monitoring

Erosive wear of the pump casings was identified as a critical issue in the design of the HIH booster station pumps. Monitoring pump wear using ultrasonic sensors fixed to the pump casing was effective. However, locating sensors in expected areas of highest wear is a challenge.

Testing during the development phase of the HIH project evaluated pump wear. Due to the high level of radioactivity and the wide variability in the sludge's characteristics, conservative test simulants were used. Testing was performed to establish an expected operational wear rate based on scaled-down test pump casing wear. A monitoring program was established with safety limits for allowable booster pump wear. Ultrasonic thickness (UT) sensors were placed on each outdoor booster station pump with the location of the sensors based on the highest areas of wear experienced during testing.

During the transfer campaign, there were two wear-related failures of a submersible transfer pump. Evaluation of the submersible pumps' design, combined with a reevaluation of test data taken early in the project, identified a potential failure mechanism associated with localized wear that occurs in the vicinity of an internal casing weld (Figure 5). The pumps include a "cavity" located just behind the edge of the impeller intended to adjust the pump performance characteristics. It was noticed in the test pumps that the highest wear area was located at the corner of the cavity, where it met the casing wall. In the case of the failed pumps, this location coincided with the weld joining the casing wall to the casing upper flange. It was surmised that the high wear area eroded the weld (not a full penetration weld) and ultimately resulted in the holes found in the pumps. Similar high wear locations in the test pump were not coincident with the location of the weld and therefore did not result in similar failures during wear testing.

The welding process itself is another potential contributor to the localized failures in the region of the welds. The HIH pumps were made of duplex stainless steel to resist erosion. The properties of duplex stainless steels can be appreciably affected by welding. Due to the importance of maintaining a balanced microstructure and avoiding the formation of undesirable metallurgical phases, the welding procedures must be properly specified and controlled. If the welding procedure is improper and disrupts the appropriate microstructure, loss of material properties can occur. The possibility of reduced wear resistance due to changes in the material caused by welding may have contributed to the HIH pump failures.

The failures of the submersible pump prompted further inspection of the above-water booster station pumps. A manual scan of the casings of the booster station pumps identified wear that was higher than that being recorded by the nine original UT sensors. The high wear was located at the edge of the

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"cavity" in those pumps as well. The casing weld was not coincident with the high wear area in the booster station pumps, so there was no immediate concern with a similar wear failure. Additional sensors were placed at the higher wear locations and those sensors were added to the wear monitoring program.

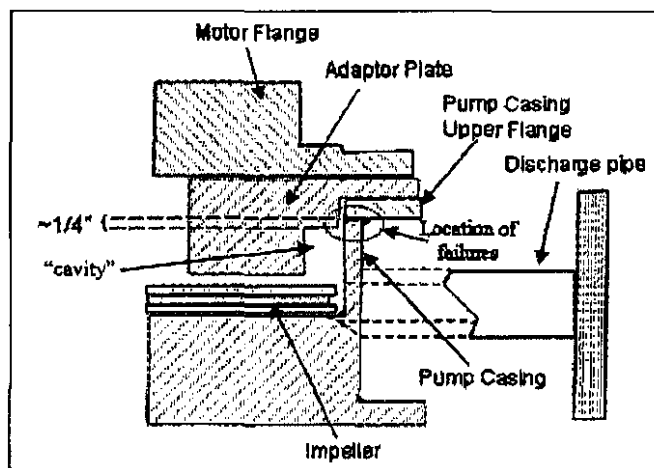


Fig. 5. This diagram indicates the location of the failure of the underwater pumps.

Lessons

It is clear from testing and operations that the constituents of the K Basin sludge cause significant wear in centrifugal pumps. However, the pump wear is highly localized and it is difficult to predict the exact location of the highest wear without testing a full-scale pump. In the case of the booster station pumps, the locations predicted from the scale model testing were not the highest wear locations in the full-scale pumps. The reason for this discrepancy is surmised to be due to the existence of the cavity behind the impeller in the booster station pumps.

The use of fixed (epoxy-mounted) UT sensors on a stainless steel wall provided reliable thickness readings that could be obtained remotely, away from the high-dose areas near the pumps. In the HIH application, it would have been impractical to make periodic hand-held readings because the pumps were shrouded with a thick steel shield.

Some problems were encountered in getting the epoxy to set when the work was being performed in the field (outdoors in cold weather). Temperature control and cleanliness is important when applying the epoxy to attach the UT sensors. If the work can be done in a controlled environment before installation, the sensors remained well attached throughout the mission.

Full-penetration welding in areas of wear should be required when procuring pumps. Weld materials should be chosen to provide equivalent resistance to the wear as the base metal.

The properties of duplex stainless steels can be appreciably affected by welding. Welding procedures must be properly specified and controlled. If the welding procedure is improper, loss of material properties such as wear resistance can occur.

Booster Station Pump Seals

Booster station pumps utilized a double mechanical seal with a pressurized barrier fluid to reduce the possibility of seal failures in the outdoor booster stations. These seal technologies brought unique challenges with respect to maintaining fluid levels and pressure in the seal reservoir during operation.

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HHH booster station pumps were conventional ASME B73.1 horizontal, single-stage, end-suction pumps with custom features. This style of pump relies on a mechanical seal to prevent leakage of process fluid through the shaft penetration. For the HHH transfer system, the highly abrasive sludge ruled out using a canned motor pump and other considerations prevented selecting positive displacement pumps without mechanical seals.

A highly reliable sealing system was needed for the HHH booster pumps due to the significant radiological impact of a seal failure. An American Petroleum Institute (API) Plan 53A double mechanical seal system was selected for the HHH booster pumps because this type of mechanical seal configuration is normally considered to provide the highest protection against entry of process fluid into the seal chamber. The API Plan 53A system utilizes a pressurized external fluid reservoir so that flow across the seal face is always from the barrier fluid to the process fluid. Due to the abrasiveness of the sludge, tungsten carbide seal faces were used on the in-board (process) side and a tungsten carbide to carbon face was deployed on the outboard (atmosphere) side.

The initial design of the HHH system did not provide a permanently mounted compressed gas recharge system for the seal fluid reservoirs. Instead, a portable, manual means of recharging each tank was required. It would typically take from 30 to 45 minutes to recharge the reservoir. During operations, loss of pressure in the reservoir tank was a frequent event and the additional labor and the lost transfer time resulting from the manual charging method became a significant inefficiency. Midway through the HHH sludge transfer, a permanent compressed gas recharge system was installed at each booster station.

Low seal fluid level alarms were received multiple times during the sludge transfer campaign due to leaks into the process system. Generally, this would occur after the pumps were shut down, but did occasionally occur during operation, resulting in a system trip. The recovery required manually refilling the reservoir during system shutdown, and using high-pressure air to "shock" the seal faces into properly reseating.

Ensuring the mechanical seals would operate within recommended limits also required installing alarms and interlocks to shut down the system. Many HHH system shutdowns were due to seal protection interlock actuations on high or low pressure. The sources of the pressure excursions were mainly attributed to causes away from the booster station pumps, such as the line being blocked, the failure of a submersible pump, or high pump vibration.

Lessons

The API Plan 53A double mechanical seal with an externally pressurized barrier fluid system proved highly reliable and should be considered on future projects where centrifugal pumps with mechanical seals are selected, and failures of the seals have significant radiological concerns. If used, seal systems should be designed for frequent fluid replenishment and adjustable pressurization.

The downside of the seal protection strategy was the high level of engineering required, the relatively high maintenance of the seal support system, and the many system trips that were directly attributable to seal protection.

Use of a data logger to track process variables is highly recommended when pump seal protection interlocks are employed. The HHH data logger proved invaluable during troubleshooting in identifying which interlock tripped, and in determining the cause of the trip.

Pumps that do not use mechanical seals, such as canned motor pumps and certain positive displacement pumps should be considered when the application allows. Mechanical seals are often a weak link in pumping systems, particularly undesirable for non-submersible pumps in radioactive waste pumping applications. Elimination of seal support systems can save significant engineering, construction, and maintenance resources, especially when multiple pumps are used.

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Booster Station Pump Vibration

During early HII testing, high vibration was observed in the table-mounted pumps and motors. The mountings were modified as the system was constructed to reduce the potential for vibration. During operations, vibration levels increased and vibration monitoring became necessary to ensure satisfactory operation.

The HII booster station pumps were placed inside of a steel enclosure to mitigate the release of radioactive material to the environment in the event of a leak. The design removed the pump/motor from the manufacturer's base mounting and placed the pump motor outside of the enclosure with a flexible coupling to the pump shaft. This configuration is a non-standard pump mounting configuration driven by the unusual requirements for containment.

A single booster pump station was tested at the fabricator's facility before the pump was delivered. The results of that testing showed that horizontal vibrations were in excess of the Hydraulic Institute Standard. A series of design modifications were made to reduce vibration and improve the pump/motor mountings. After the booster stations were installed, additional testing showed decreased horizontal vibrations but also showed increased axial vibrations in excess of the Hydraulics Institute standard. These results drove additional field modifications of the pump/motor mounting in the field.

Midway through the HII transfer operations, high vibration was observed in one of the booster stations. In response, vibration sensors were permanently fixed to the three axes on each of the booster station pumps and a monitoring program was implemented. The monitoring program defined thresholds for pump operation and monitoring frequency to ensure that vibration levels did not increase over time without being detected. The main concerns with excessive vibration levels were the integrity of the pump seal and piping or structural failures.

In some instances during operation, vibration levels would increase marginally and hourly surveillance was performed. In this case, slurry transfer was allowed to continue. In other cases, vibration levels increased to levels that required the system to be stopped. Typical responses included checking equipment, tightening mounting supports, or changing operating speeds to reduce the vibration.

The root cause of the vibration issues on the booster pump stations was associated with the mounting of the pumps and motors. In addition, buildup of particulate on the vanes of the pump's impeller (see discussion of pump fouling) clearly contributed to increased vibration during operation. Modal analysis of the booster station structure, including the pump stands, showed resonance frequencies near the rotational frequency of the pumps at operating speeds. Typically, pumps and their motors are mounted to a monolithic base (usually a concrete slab) to eliminate external resonance effects.

Lessons

Future projects should pay attention to the mounting configuration of all rotating equipment during the design phase. In the case of the HII booster pumps, a monolithic base of thick steel that would span across the station wall and hold both pump and the stiffening of the table supports would have been a better option for the pumps/motors.

Future projects using centrifugal pumps to transfer radioactive waste should install vibration sensors on the pump assembly to allow for remote monitoring.

Fouling of Booster Station Pump

HII-P-302 exhibited high vibration, and ultimately, was found to have one impeller cavity fully blocked by sludge buildup. Determination of the causes and recovery were time consuming. Analysis indicated a potential design flaw in the impeller.

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During HHH transfer operations in January 2007, personnel observed significant increases in vibration from three of the four booster pumps. The vibration at one pump was so severe the transfer was shut down to prevent the pump from failing. At that time, transfer of KE sludge was less than 20 percent complete. Although each HHH booster station contained an installed spare pump, the onset of unacceptably high vibration that early in the transfer process caused legitimate concern. No spare booster pumps were on hand and the long lead time associated with procuring new pumps brought significant risk that the HHH project would not be completed on schedule.

Several days prior to the pump shutdown, a five percent reduction in the pump head was noted. At the time of pump shutdown, the booster pumps were not equipped with vibration sensors. Vibration sensors were installed and the pump was operated in an unsuccessful attempt to flush out any debris. Analysis of the vibration data concluded that the resonance was originating from the pump's impeller, possibly due to the impeller's mounting being loose or fouling by foreign objects. Based on this conclusion, an effort was initiated to inspect the pump internals using a boroscope.

The boroscope inspection revealed accumulations of process sludge within the pump's closed impeller. Inspection through the discharge of the pump showed the trailing edges of all five vanes had a mixed composition of solid particles packed tightly along their trailing edge. Inspection through the inlet eye of the pump revealed a buildup of solids in one of the five impeller passageways (Figure 6). This passage was fully bridged with sludge and is the likely cause of the severe vibration experienced on this pump. The pump impeller design quickly became the focus of investigation.

The manufacturer's drawings submitted as part of the pump procurement did not show the details of impeller construction. A review of the drawings, once obtained, identified the impeller's very narrow, only 0.635 cm (0.25-inch) wide, and highly wrapped (approximately 240°) vanes, as can be seen in Figure 6. The narrow closed vanes were a surprise to the project engineers, as particles up to 0.635 cm (0.25-inch) were known to be in the sludge.

The impeller rotates counter-clockwise as viewed looking at the pump inlet. The long, highly wrapped vanes of the pump are believed to allow heavy particles to "stick" along the underside surface of the vane, where the tangent to the vane surface is close to 90 degrees from a radial line. The radial forces generated at that location tend to compact the sludge, while the flow velocity adjacent to this surface is low. These combined effects can lead to the accumulation of sludge along the underside of the vane.

To help confirm the theory, an independent computational fluid dynamic (CFD) analysis of the impeller was performed. The CFD analysis confirmed a flow recirculation pattern on the trailing face of the vane in the location as where the solids accumulations in the fouled pump were observed.

The CFD analysis was not able to definitively predict if sludge accumulation and growth would occur, but the recirculation along the vane can be interpreted as favorable for its occurrence. The conclusion was the impeller passage plugging stemmed more from inadequate clearance through the impeller (i.e., allowing objects 0.635 cm or larger into the pump) than the internal recirculation patterns along the vanes.

This conclusion appears to have been borne out by completion of the HHH transfer without recurrence of severe vibration attributable to fouling after installation of upstream 0.476 cm (3/16 inch) strainers in the system.

Lessons

The procurement specification had unrealistic requirements for hydraulic performance for a centrifugal slurry pump. The project required that the pump be a relatively small end-suction (single-stage) pump, in accordance with ASME B73.1, and that it produce a very high head (~ 200 m [700 ft] of head) while pumping slurry. No other slurry pump manufacturer was found that could generate more than half of that pump head with a centrifugal pump. Only one pump vendor made an offering in response to the request for proposal, which should also have raised suspicion about the specification requirements.

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Procurements of pumps for transferring sludge should require the manufacturer to disclose the details of the internal dimensions. The impeller for the HHH booster station pump was designed with 0.635-cm (0.25-inch) wide closed vane passages, yet the HHH slurry could contain material up to 0.635-cm (0.25-inch) diameter. The pump vendor did not provide the internal dimensions of the pump until after fouling was suspected. The vendor data sheets stated that 0.635-cm (0.25-inch) particulate could be transferred by the pumps. Most slurry pump manufacturers use a 1.5:1 or 2:1 margin between the largest sphere that can be passed through the pump and the width of the impeller vanes.

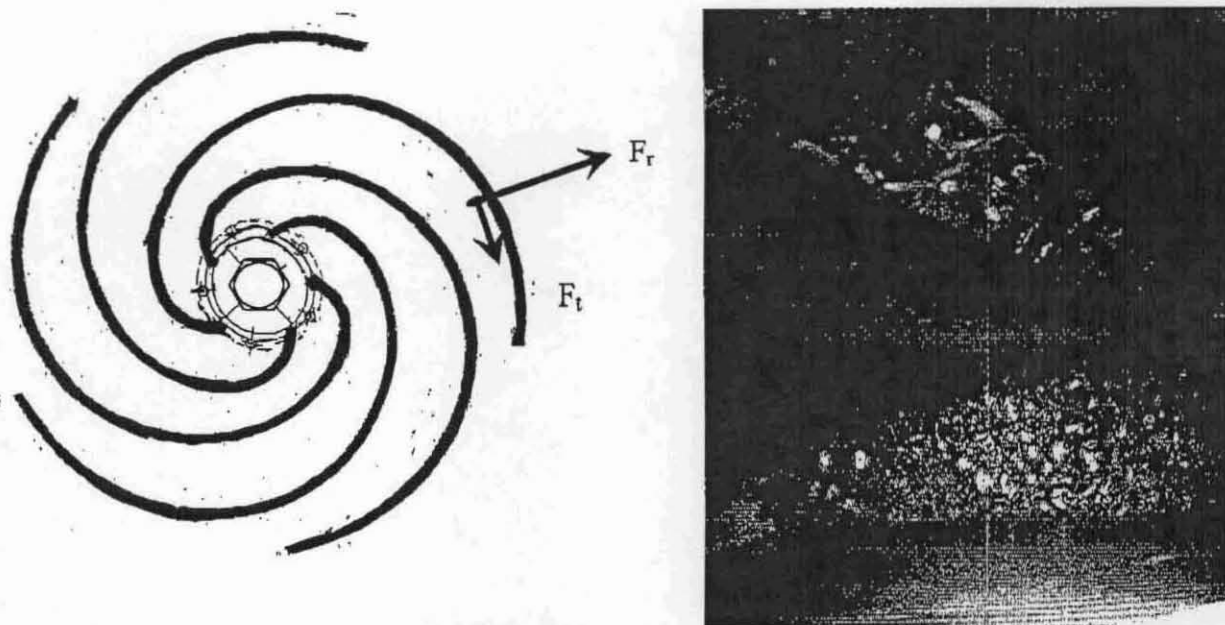


Fig. 6. The diagram on the left is a sketch of the HHH impeller with radial and tangential forces. The photograph on the right shows the underside of a fouled pump vane (top) and bridged vane passage viewed from pump inlet (bottom).

Pumps with highly wrapped impeller vanes should not be selected for slurry applications because of the potential for collecting material on the vanes.

Designs for system pumping slurry should combine pump internal clearances with slurry particle size control to prevent fouling. After strainers were installed, the HHH transfer was completed without recurrence of severe vibration attributable to fouling.

The presence of an installed secondary booster pump in each Booster Station proved invaluable to completing the transfer. At HHH transfer completion, all four secondary booster pumps were in operation.

Future projects should consider a trip condition that would transition the system to a flush mode and possibly a speed reduction instead of a full stop so that slurry buildup is reduced or eliminated whenever possible. Major vibration indications induced by material deposition on the impeller vanes, seemed to occur immediately after HHH system trip conditions, stopping the pump with slurry in the lines and pumps.

Data Acquisition during Operations

The inclusion of a data logger to monitor and record operational parameters proved to be an invaluable tool for diagnosis of problems.

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The project utilized a data acquisition unit, or data logger, to display and record several HIIH system variables. This unit was instrumental in the success of the project. It was used for routine operations as well as diagnosis of problems during start-up and system trips during sludge transfer operations. With seven centrifugal pumps operating in series, it can be impossible to determine the cause of transients or the source of system trips in real time. Only through review of data traces obtained from the data logger were HIIH system engineers able to troubleshoot the system effectively.

The flexibility of the data logger to display and record data was a major factor in its selection and use. The following features of the data logger were very useful during this project:

- Input channels: Of the 30 analog input channels, all but four were used.
- Math channels: The unit had another 30 math channels available. Math channels take signals from one or more of the input channels and perform a user selected mathematical function. All but three of these channels were used.
- Multiple user configurable screens: The user has a choice of how to display the data being monitored and recorded. The digital and trend were the two most useful screens for the HIIH project.
- Data card: The data logger stored recorded data in a memory buffer. The data was transferred to a removable memory card periodically. This feature was essential in getting the data from the data logger transferred to a desktop computer for review and analysis.
- Support software: The HIIH project had support software to display and analyze the recorded data using a personal computer. This aspect of the data logger system was very useful for trouble shooting, tuning, and analyses of the HIIH system.
- Sampling/recording intervals: Complicated and sensitive hydraulic system data recording at a relatively rapid (1 second) rate allowed for data analysis and troubleshooting that may have been impossible if larger sampling/recording intervals were used.

Lessons

A data logger is essential for troubleshooting transients in a moderately complex process system.

Allow for expansion. Including 10-20 percent extra channels is recommended. Early in the design process, the decision was made to double the number of channels available on the HIIH data logger. This proved to be a wise choice as more signals were connected to the data logger as the design process continued.

Lock and Tag

Consideration of Lock and Tag boundaries and locations during the design may save significant time during system operation and maintenance.

The HIIH system operated within and between the two K Basins spaced greater than 400 meters (¼ mile) apart. Many of the components within the HIIH system had multiple power supplies located in different facilities. The process of hanging Lock and Tag for maintenance in different facilities which were posted as airborne radiation areas required substantial time and planning.

Lessons

When designing a system, incorporate provisions for lock and tag. Some items of note are:

- "Plug-in" items that can be under the exclusive control of the worker should be used wherever possible.
- Multiple power sources within a panel should be avoided if possible.

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- The placement of electrical power supplies outside of airborne radiation and contamination areas is desirable. The expense of additional conduit will be offset by the time saved performing maintenance and hazardous energy isolation.
- Isolation valves should be provided on the suction and discharge of every pump.
- Isolation valves should be provided for every gauge.
- If isolation valves are anticipated to be throttled during operation, an additional isolation valve should be installed in series.

CONCLUSION

Design estimates of the duration anticipated to transfer all sludge out of KE Basin were on the order of 40 hours. Ultimately, the operation took seven months. The difference between these durations reflects the level of difficulty encountered in completing the HH project. Valuable lessons were learned, as discussed in this paper, which may help future projects that undertake similar campaigns.

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